

# Introduction and Overview of Mineral Deposit Modeling

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## INTRODUCTION

Activities in mineral deposit modeling have continued to develop on several fronts since the publication of "Mineral Deposit Models," edited by Cox and Singer (1986). That bulletin is a collection of 87 descriptive deposit models and 60 grade and tonnage models prepared by many authors both from within and outside of the U.S. Geological Survey. The present bulletin continues that effort with the addition of new or revised models. Before these models are introduced, a review of modeling as used here is provided as well as an overview of mineral deposit modeling since the publication of Cox and Singer (1986).

## EXPLANATION OF DESCRIPTIVE AND GRADE AND TONNAGE MODELS

A general definition of a mineral deposit model as found in Cox and Singer (1986, p. 2) is "the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits. The model may be empirical (descriptive), in which instance the various attributes are recognized as essential even though their relationships are unknown; or it may be theoretical (genetic), in which instance the attributes are interrelated through some fundamental concept."

With a descriptive model in hand, member deposits can be recognized and their size and grades can be used to develop a grade and tonnage model. Ideally, the data should be the estimated premining tonnages and grades. Estimates should be for the tonnage at the lowest cutoff grades. The grade and tonnage model is presented in a graphical format in order to make it easy to display the data and to compare this type of deposit with other deposit types (Cox and Singer, 1986). The plots (figs. 2-19, 21, 22, 25-34) show either grade or tonnage on the horizontal axis, whereas the vertical axis is always the cumula-

tive proportion of deposits. The units are all metric, and a logarithmic scale is used for tonnage and most grades. Each dot represents an individual deposit, and the deposits are cumulated in ascending grade or tonnage. Owing to limitations in the plot routine, a point will not be shown on the plot if it has exactly the same value as the vertical axis (for example, the Keystone-Union deposit is not displayed in figure 12). On rare occasions, values less than the value of the vertical axis are not shown as well (for example, Hog Ranch is not displayed in figure 16). Smoothed curves, representing percentiles of a lognormal distribution that has the same mean and standard deviation as the observed data, are plotted through the points. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distributions are constructed.

## OVERVIEW OF PAPERS ON DEPOSIT MODELING

A number of papers on deposit modeling and support data have been published in various places since 1986. These papers focus on descriptive deposit models and (or) grade and tonnage models that are useful for resource assessments. Some of the papers document the models originally published in Cox and Singer (1986), others attempt to improve the models' applicability in resource assessments, and still others present new deposit models. The following overview is presented chronologically by type of study. Model numbers shown in parentheses follow the format used in Cox and Singer (1986), with some modifications.

Several papers not cited in Cox and Singer (1986) document the data used in some of the grade and tonnage models. Orris (1985) provided data for 93 bedded barite deposits (No. 31b), of which less than 30 had grade and tonnage information. Additional tabulated data for each deposit include volume of deposit, associated minerals, host formation, host age, host lithology, and references. Orris and Bliss (1985) provided data for 330 gold placers (No. 39a). The data for each deposit include placer type, mining method(s), production history, bedrock source, and

references. Bagby and Berger (1986) presented data for 31 of the deposits used in the grade and tonnage model for carbonate-hosted Au-Ag (No. 26a) and discussed the geologic characteristics of the deposit type, which (in order to accommodate the noncarbonate host rocks) they called the sediment-hosted, disseminated precious-metal deposits. A number of tables provide information on host rocks, igneous rocks, structure, mineralization age, alteration, ore bodies (form, mineralogy, gold or silver site, veins), trace-element geochemistry, tonnage, grades, and references for selected deposits. Also included are plots of trace-element variations, sulfur isotopic variation in sulfides and barite, gold grade versus tonnage, and cumulative frequency distributions of tonnages and grades. Bliss and Jones (1988) provided data for 357 deposits used to develop the grade and tonnage model for low-sulfide Au-quartz veins (No. 36a). Tabulated data for each deposit include tonnage, grades, mineralogy, and references. This paper also evaluated the frequency of occurrence, order of abundance, and assemblages of ore minerals, and displayed the results in tables and pie diagrams.

Grade and tonnage models can provide insight into geologic processes. A paper by Mosier and others (1986) documented three types of epithermal gold-quartz-adularia deposits, based on the types of basement rocks underlying the host volcanic pile. The Sado type (No. 25d) occurs over an igneous-dominant basement, the Comstock type (No. 25c) over a sedimentary-dominant basement, and the Creede type (No. 25b) over a saline-carbonate-dominant basement. Each type has different tonnages and grades, particularly among the base metals. These models indicate that basement rocks probably influence the character of the ore fluids. Grade and tonnage models are shown for the three deposit types. Tabulated data for each district include tonnage, grades, basement rocks, and references. A study by Page and others (1986) examined the platinum-group element values of 250 deposits used in the grade and tonnage model for minor podiform chromite deposits (No. 8a) to test for homogeneity of platinum-group elements within the deposit type. Analysis of variance of platinum-group element content demonstrated that deposits within terranes were not significantly different. Relatively small but significant differences in the combined medians for Ir, Ru, Rh, and Pt exist (at the 1 percent level) among terranes, but the reasons for these differences are not clear. Also, it was discovered that the platinum-group element abundances of minor podiform chromite deposits are similar to those of major podiform chromite deposits (No. 8b). A part of the analysis of platinum-group elements is tabulated, and grade models for individual platinum-group elements are shown.

There are three new descriptive deposit models based on one or two examples. These new models have not been included in this bulletin because they do not have

associated grade and tonnage models. Cox and Rytuba (1987) developed a descriptive model for Lihir Island gold (No. 25), a gold deposit occurring in the root of a volcanic center. This deposit, in Papua New Guinea, is the only known example of its type. Tosdal and Smith (1987) developed two descriptive models for deposits in regionally metamorphosed eugeosynclinal rocks. (The model numbers assigned to these models should have been 36 rather than 37, in that they are not hosted in metasedimentary rocks.) First, the gneiss-hosted gold model (No. 37c) is based on the Tumco mine group and American Girl-Padrey Madre mines in the Cargo Muchaco Mountains, southeastern California. This deposit type either occurs in lenticular bodies of biotite-magnetite-quartz gneiss of volcanic or granitic origin, subparallel to the gneissic foliation, or is associated with low-angle ductile shear zones. Second, the gneiss-hosted epithermal gold model (37d) is based on the Mesquite mine, southern California, which occurs in breccia fillings, fracture fillings, and high-angle veins that cut subhorizontal amphibolite-facies metavolcanic gneiss and plutonic gneiss. The Mesquite deposit is similar to epithermal quartz-adularia-gold vein deposits (Sado type?), except that it is hosted in metaigneous rocks—this raises the question of whether or not it should be treated as another type of deposit.

Attempts to distinguish subtypes within existing deposit models have been carried out in several papers. Heald and others (1987) successfully distinguished two types of volcanic-hosted epithermal precious- and base-metal deposits through a detailed examination of the characteristics of 17 well-documented districts. These characteristics include the ore, gangue, and alteration mineral assemblages; the spatial and temporal distributions of mineral assemblages; the host-rock composition; the age relations between ore deposition and emplacement of the host rock; the size of the district; the temperatures of mineral deposition; the chemical composition and origin of the fluids; the paleodepth estimates; and the regional geologic setting. Differences in many of these characteristics were documented in the two major types designated the acid-sulfate type and the adularia-sericite type. It was found that the two most important factors for distinguishing these types are (1) the vein and alteration mineral assemblages and (2) the age relations between ore deposition and emplacement of the host rock. Bliss and others (1987) examined gold grades and volumes to distinguish among gold placer types but found that they could not distinguish most types of gold placers, except for the alluvial-plain and fan placers. However, when these data were coupled with mining methods, estimates could be made of the amount of gold remaining when a placer mine changes from small-volume mining (such as panning, sluicing, or drift mining) to large-volume mining (such as dredging or hydraulic mining). New descriptive and grade and tonnage models

for two subtypes of Au-bearing skarn deposits were designated Au skarn and byproduct Au skarn (Orris and others, 1987; Theodore and others, 1990). Although the two subtypes do not differ in geologic characteristics or tonnages, there are significant differences in the median gold and silver grades. Tabulated data which are largely overlapping can be found in both Orris and others (1987) and Theodore and others (1990). Data tables give name, location (mining district), formation age/name, igneous rocks, age, ore minerals, gangue minerals, ore control, tonnage, gold grade, silver grade, base metal grades, comments and references. Cox and Singer (1988) examined the distribution of gold in three types of porphyry copper deposits designated as porphyry copper-gold (No. 20c), porphyry copper-gold-molybdenum (No. 17), and porphyry copper-molybdenum (No. 21a). This paper defines the three types of porphyry copper deposit models used in Cox and Singer (1986). It was concluded that gold content alone could not define porphyry copper-gold systems, but that the three types differed significantly in Cu-MO-AU content, magnetite content, deposit morphology, depth of emplacement, and tonnage. Mosier and Page (1988) distinguished among four subtypes of volcanogenic manganese deposits (No. 24c) based on tectonic environments. These subtypes are supported by differences in tonnage, grades, volume, lithology, mineralogy, and deposit morphology. The new models—called Franciscan (No. 24c.1), Cuban (No. 24c.2), Olympic Peninsula (No. 24c.3), and Cyprus (No. 24c.4)—each have individual descriptive and grade and tonnage models and mineral-deposit density values.

Berger and Singer (1987) developed a new grade and tonnage model for hot-spring gold-silver deposits (No. 25a) based on 10 deposits in Nevada and California.

The importance of industrial minerals in economic development has been long recognized in national and international assessments and commonly far exceeds that of fuels and metals. However, they usually receive only a passing reference. This is because, in part, they cannot always be modeled using standard grade-tonnage models. Orris and Bliss (1989) took a step in resolving this impasse by formally defining three new model types for describing industrial mineral deposits. These include (1) the contained-material model applicable to commodities where the material must meet a minimum level of purity (for example, feldspars, travertine); (2) the impurity model for commodities where the distribution of impurities affects utilization (for example, iron or aluminum in glass sand); and (3) the deposit-specific model applicable to commodities that are unique (for example, the distribution of the proportion of gem-quality diamonds, and the average diamond size in diamond kimberlite pipes). Descriptive models of 22 industrial mineral deposit types prepared by 13 contributors can be found in a report edited by Orris and Bliss (1991). Sutphin and Bliss (1990) compared amor-

phous and disseminated deposit types using graphite grade, tonnage, and contained carbon. While differences are clearly present in the carbon grade and tonnage between the two types, this was not the case for contained carbon.

A graphic method was developed by Bliss and others (1990) to show how tonnage data can be used to guide in the selection among the 71 deposit types (with grade and tonnage models) during the search for deposits amenable to small-scale mining. McKelvey and Bliss (1991) compared the contained copper, lead, zinc, gold, and (or) silver of a median deposit for all deposit types having grade and tonnage models with the 1989 world production of copper, lead, zinc, gold, and silver. This work shows the importance of porphyry deposit types as a source of most of these metals.

## NEW DEVELOPMENTS IN DEPOSIT MODELING

This volume will be one of several pertaining to developments in deposit modeling. Future volumes will include studies on predictive resource assessments, exploration modeling, and spatial modeling. Here, we present six new descriptive models, nine new or revised grade and tonnage models, and a numerical method of matching mineral deposits to deposit models. New descriptive models were developed for thorium-rare-earth veins (No. 1ld), distal disseminated Ag-Au (No. 19c), solution-collapse breccia pipe uranium deposits (No. 32e), oolitic ironstones (No. 34f), laterite-saprolite Au (No. 38g), and detachment-fault base and precious metals (No. 40a). New grade and tonnage models include thorium-rare-earth veins (No. 1ld), distal disseminated Ag-Au (No. 19c), Sierran kuroko (28a.1), solution-collapse breccia pipe uranium deposits (No. 32e), oolitic ironstones (No. 34f), Chugach-type low-sulfide Au-quartz veins (36a.1), and laterite-saprolite Au (No. 38g). Revised existing grade and tonnage models include hot-spring Au-Ag (No. 25a) and sediment-hosted Au (No. 26a). The principal use of grade and tonnage models is for making quantitative mineral resource assessments. A recent example can be found in a paper by Reed and others (1989) for the Seward Peninsula, Alaska. They used grade and tonnage models for Sn skarns (Menzie and Reed, 1986a), replacement Sn (Menzie and Reed, 1986b), Sn veins (Menzie and Reed, 1986c), and Sn greisen (Menzie and Reed, 1986d). These models, together with estimates of the number of undiscovered deposits, allow computer simulations to be made that estimate the amount of Sn in undiscovered deposits of the Seward Peninsula.

A new development by R.B. McCammon is the numerical characterization of deposit models. This method can be used to assign the appropriate deposit type to a target mineral deposit, permitting a quantitative matching of the description of a mineral deposit to

one or more descriptive models. To facilitate the scoring used to do this, worksheets are provided for each of the descriptive models found in Cox and Singer (1986).

The descriptive model of thorium-rare-earth veins (No. 11d), by Mortimer Staatz, is based on data from North American deposits. The grade and tonnage model of thorium-rare-earth veins by J.D. Bliss is different from those developed for most other deposit types modeled to date in that none of the thorium-rare-earth deposits have been mined extensively. Instead of using grades and tonnages from production plus reserves plus resources, the model is based on estimates of size of unworked veins and the median values of rock analyses. The grade and tonnage model is based on 28 deposits in the United States and one in Mexico.

The descriptive model of distal disseminated Ag-Au (No. 19c) by D.P. Cox, was developed during the analysis of Nevada's resources project for deposits that (1) are richer in Ag relative to Au, (2) contain Zn, Pb, Cu, and Mn, (3) occur near igneous intrusions, and (4) are distally associated with skarns and polymetallic veins and replacements. Some of these deposits were formerly classified as carbonate-hosted Au-Ag deposits (No. 26a; Berger, 1986a). The grade and tonnage model, by D.P. Cox and D.A. Singer, is based on data for 10 deposits from the United States, Mexico, and Peru.

The grade and tonnage model of hot-spring Au-Ag (No. 25a), by B.R. Berger and D.A. Singer, is a revision of an earlier model by Berger and Singer (1987). It is in response to the availability of grade and tonnage data for more deposits and of revised data for others.

The grade and tonnage model of sediment-hosted Au (No. 26a), by D.L. Mosier, D.A. Singer, W.C. Bagby, and W.D. Menzie, is a revision of an earlier model by Bagby and others (1986). It is in response to the availability of grade and tonnage data for more deposits and to a new definition for a deposit, which combined or separated some deposits. The result of this new descriptive definition is that some deposits included in the earlier model have been reassigned to distal disseminated Ag-Au (No. 19c) by D.P. Cox.

The grade and tonnage model of Sierran kuroko deposits (No. 28a.1), by D.A. Singer, was developed because Triassic or Jurassic deposits of the kuroko massive sulfide (No. 28a) in North America and, perhaps, South America are significantly smaller than the worldwide kuroko group as described by Singer and Mosier (1986).

The descriptive model of solution-collapse breccia pipe uranium deposits (No. 32e), by W.I. Finch, is based on deposits from the Colorado Plateau of Arizona. This deposit type is most likely an important future source of uranium. The grade and tonnage model, by W.I. Finch, C.T. Pierson, and H.B. Sutphin, is developed from data on eight deposits in Arizona. The model is atypical in that the

deposit tonnages have a very narrow range and the lognormal distribution was rejected. This is also true for uranium oxide grades.

The descriptive model of oolitic ironstones (No. 34f), by J.B. Maynard and F.B. Van Houton, is an important addition to the two existing descriptive models for iron deposits including Superior Fe (Cannon, 1986b) and Algoma Fe (Cannon, 1986a). The grade and tonnage model of oolitic ironstones, by G.J. Orris, is based on 40 deposits from North and South America, Europe, and China.

The grade and tonnage model of Chugach-type low-sulfide Au-quartz veins (No. 36a.1), by J.D. Bliss, was developed because low-sulfide Au-quartz veins in and adjacent to the Chugach National Forest, Alaska, are significantly smaller and have lower Au grades than the low-sulfide Au-quartz veins (No. 36a) elsewhere in the world (modeled by Bliss, 1986). This model and the previous one developed for kuroko massive sulfide exemplify the flexibility of grade and tonnage models in conforming to a specific geologic criterion that is observed but for which the reasons are not yet clear. These and other identified subtypes represent opportunities to identify either economic and (or) geologic factors causing these differences.

Au placers have been classified using various criteria, including types and modes of transport. Placers are identified as "alluvial" when concentration has occurred in streams and rivers, "colluvial" when Au has been transported with surface material by downhill creep away from the bedrock source, and "eluvial" when a deposit develops in situ over or adjacent to the bedrock sources (Boyle, 1979). The descriptive model of laterite-saprolite Au (No. 38g), by G.E. McKelvey, is of the latter type, but it is a type that develops primarily from chemical rather than physical processes. Because these deposits develop chemically, they have been classified here as a residual rather than a depositional type of deposit. This continuum between the two types is an enigma in classification schemes and should really be represented by both types-hence its inclusion in parentheses in the depositional type of deposit (see app. A). Au is transported in water under near-surface temperature and pressure conditions, and deposition appears to be controlled by ground-water levels in areas that have or have had tropical and subtropical climate conditions. The ubiquitous nature and the hydrogeologic and paleoclimatic constraints of this deposit type could affect the applicability of the model (depending, of course, on the level of information available) in resource assessments. The deposits used in the grade and tonnage model of laterite-saprolite Au, by J.D. Bliss, are based on the model (No. 38g) by G.E. McKelvey. The grade and tonnage model is developed from data on nine, some which are poorly defined, deposits from Guyana, Western Australia, and Suriname. Like the thorium-rare-earth model (No. 11d), these deposits have yet to be worked extensively.

The preliminary descriptive model of detachment-fault-related polymetallic deposits (No. 40a), by K.R. Long, is part of the continued effort to effectively describe this emerging deposit type(s). The model is preceded by a paper giving an evaluation of available descriptive and grade-tonnage data, including a list of distinguishing characteristics of detachment-fault-related mineralization. Also given is a list of deposit types commonly confused with detachment-fault-related mineralization. The descriptive model of gold on flat faults (No. 37b) by Bouley (1986) is an earlier model for this deposit type. An important revision of this model, using lithologic-tectonic environment criteria of Cox and Singer (1986, table 1), is its reclassification into the new categories of "Regional Geologic Structures" and "Extended Terranes" (see app. A).

Each of the grade and tonnage models presented in this bulletin is accompanied by a list of the deposits, locations, and, in some cases, the grade and tonnage data. The location is shown by an abbreviated form that identifies either the country or the country plus a state or province. A list of abbreviations is provided in appendix B.

Descriptive and grade and tonnage models are useful in mineral resource assessments, but, as demonstrated in these studies, they may have wider applications. Not only do these models help to define the many deposit types present, but they also help to decipher the complexities of mineral concentrations and provide insight on the genetic or geologic processes responsible for their formation.